

Enhanced di-photon Higgs signal in the Next-to-Minimal Supersymmetric Standard Model

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Abstract

In the Next-to-Minimal Supersymmetric Standard Model, CP-even Higgs bosons can have masses in the range of $80 - 110$ GeV in agreement with constraints from LEP due to their sizeable singlet component. Nevertheless their branching ratio into two photons can be more than 10 times larger than the one of a Standard Model Higgs boson of similar mass due to a reduced coupling to b quarks. This can lead to a spectacular enhancement of the Higgs signal rate in the di-photon channel at hadron colliders by a factor 6. Corresponding scenarios can occur in the Next-to-Minimal Supersymmetric Standard Model for a relatively low Susy breaking scale.

1 Introduction

One of the main motivations of the LHC is the search for the Higgs boson in the Standard Model (SM) of fundamental interactions or, if realized in nature, the search for at least one of several Higgs bosons in corresponding extensions of the SM as by supersymmetry (Susy).

In order to separate possible signals for Higgs bosons from the background, the experimental groups have to make assumptions on its production modes, decays and masses. Production modes and decays are quite well known for the SM, and most of its Susy extensions. Of course, the experimental groups concentrate on Higgs masses M_H which are not in conflict with unsuccessful searches for Higgs bosons at LEP, typically $M_H \gtrsim 110$ GeV [1] or $M_H \gtrsim 115$ GeV [2] both within the SM and the Minimal Supersymmetric Standard Model (MSSM).

It is well known that, in minimal or general supersymmetric extensions of the SM, lighter Higgs bosons can exist without contradiction with LEP bounds. However, usually it is assumed that these are too difficult to detect at the LHC since, due to LEP bounds, their production rates must be reduced with respect to the SM. In the present paper we point out that this reasoning can be wrong: inspite of a somewhat reduced production rate, Higgs bosons with a mass well below 110 GeV can be compatible with LEP bounds *and* be visible at hadron colliders due to an enhanced branching ratio into the particularly clean di-photon channel: $H \rightarrow \gamma\gamma$. In this channel, the separation of a Higgs signal from the background is particularly efficient, and it would be desirable if the present studies for Higgs detection in this channel would be extended to this lower mass range.

Most importantly, corresponding scenarios can be realized in a Susy extension of the SM where one of the motivations for Susy (the solution of the finetuning problem) is solved in a particularly efficient way, since the Susy breaking scale can be relatively low. This Susy extension is the Next-to-Minimal Supersymmetric Standard Model (NMSSM).

The NMSSM is the simplest supersymmetric (Susy) extension of the SM with a scale invariant superpotential, i.e. where the only dimensionful parameters are the soft Susy breaking terms. No supersymmetric Higgs mass term μ is required, since it is generated dynamically by the vacuum expectation value (vev) of a gauge singlet superfield S . Together with the neutral components of the two SU(2) doublet Higgs fields H_u and H_d of the MSSM, one finds three neutral CP-even Higgs states in this model (see [3, 4] for recent reviews of the NMSSM). These three states mix in the form of a 3×3 mass matrix and, accordingly, the physical eigenstates are superpositions of the neutral CP-even components of H_u , H_d and S . (Here and below we assume no CP-violation in the Higgs sector.) In general, the couplings of the physical states to gauge bosons, quarks and leptons differ considerably from the corresponding couplings of a SM Higgs boson.

In the MSSM, the absence of a Higgs signal at LEP [5] imposes severe restrictions on the viable parameter space: at tree level, a SM-like Higgs state (with nearly SM-like couplings to gauge bosons) would have a mass below M_Z , which is by far excluded. Radiative corrections to the Higgs potential can lift the corresponding Higgs mass above the LEP limits; however, to this end relatively large soft Susy breaking terms in the form of stop masses close to 1 TeV are required, which implies a “little fine tuning problem”: the natural value for the negative Higgs mass term $-m_{H_u}^2$ in the Higgs potential (not to be confused with a physical Higgs mass) is of the order of the stop masses, which would naturally generate a vev $v_u \equiv \langle H_u \rangle$

of $\mathcal{O}(1 \text{ TeV})$ (instead of $\mathcal{O}(M_Z)$) unless $-m_{H_u}^2$ is compensated to a large extent by other terms in the Higgs potential. This requires a tuning of parameters of $\mathcal{O}(1\%)$.

This problem is alleviated in the NMSSM: first, the additional Higgs singlet-doublet coupling λ in the superpotential of the NMSSM allows for a tree level mass of the SM-like Higgs state above M_Z , provided $\tan\beta \equiv v_u/v_d$ is not too large [3, 4]. Second, a Higgs state with a sizeable singlet component can have a mass well below the lower LEP-bound of 114.7 GeV on a SM-like Higgs mass [6–8], without violating corresponding constraints [5] on its coupling to the Z boson. (Here we do not consider regions in parameter space where unconventional Higgs decays here could be possible.) In this case, the mass of the next-to-lightest Higgs state of the NMSSM is naturally above the LEP bound. Most importantly, these NMSSM-specific scenarios do not require large soft Susy breaking terms.

In the present paper we point out that a Higgs state with a mass in the 80–110 GeV region can have an up to 13 times larger branching ratio into two photons compared to a SM-like Higgs boson of similar mass, and a 6 times larger signal rate at hadron colliders. (Around 100 GeV, a light excess of events in the $b\bar{b}$ final state has been observed at LEP [5].) In spite of a large singlet component of such a state, this phenomenon is made possible due to a strong reduction of its coupling to $b\bar{b}$, and a corresponding reduction of its total width.

Di-photon Higgs signals at the LHC in the NMSSM have been studied before in [9]. This study concentrated on the possible detection of several of the Higgs states in the NMSSM, and on scenarios where the mass of a NMSSM Higgs boson is larger than in the MSSM which are distinct from the parameter region investigated here. In [10], di-photon Higgs signals of the MSSM, NMSSM and nMSSM are compared under the assumption of unified soft Susy breaking terms and the correct dark matter relic density, which seems to exclude again the parameter region investigated here.

In principle, a reduced coupling of a light Higgs to $b\bar{b}$ is possible in the MSSM as well [11, 12] if the lighter physical Higgs state is essentially H_u -like (i.e. without a H_d -component). There, however, this could only occur for large $\tan\beta$, larger Higgs masses (due to LEP constraints) and in a particularly tuned region in parameter space. In the NMSSM, due to the presence of the singlet, a small H_d -component of a light physical Higgs state is more natural.

Nevertheless, a large signal rate for a Higgs state with a large singlet component seems paradoxical. In the next section we discuss, after a brief introduction into the model, the couplings of Higgs states in the corresponding region of the parameter space of the NMSSM. This allows to understand the origin of the Higgs decay branching ratios as well as their production rate in gluon fusion. The last section is dedicated to conclusions and an outlook.

2 Properties of light Higgs bosons in the NMSSM

The NMSSM differs from the MSSM by the presence of the gauge singlet superfield S . The Higgs mass term $\mu H_u H_d$ in the superpotential W_{MSSM} of the MSSM is replaced by a coupling λ of H_u and H_d to S and a self-coupling κS^3 , hence the superpotential W_{NMSSM}

is scale invariant:

$$W_{NMSSM} = \lambda S H_u H_d + \frac{\kappa}{3} S^3 + h_t H_u \cdot Q_3 T_R^c + h_b H_d \cdot Q_3 B_R^c + h_\tau H_d \cdot L_3 \tau_R^c \quad (1)$$

where we have confined ourselves to the Yukawa couplings of H_u and H_d to the quarks and leptons Q_3, T_R, B_R, L_3 and τ_R of the third generation and, for the first and the last time, the fields denote superfields. Once S assumes a vev s , the first term in W_{NMSSM} generates an effective μ -term

$$\mu_{eff} = \lambda s. \quad (2)$$

Apart from the Yukawa couplings and the standard gauge interactions, the Lagrangian of the NMSSM contains soft Susy breaking terms in the form of gaugino masses M_1, M_2 and M_3 for the bino, the winos and the gluino, respectively, mass terms for all scalars (squarks, sleptons, Higgs bosons including the singlet S) as well as trilinear scalar self-couplings as $\lambda A_\lambda S H_u H_d, \frac{\kappa}{3} A_\kappa S^3, h_t A_t H_u \cdot Q_3 T_R^c, h_b A_b H_d \cdot Q_3 B_R^c$ and $h_\tau A_\tau H_d \cdot L_3 \tau_R^c$. It is convenient to replace the three soft Susy breaking mass terms $m_{H_u}^2, m_{H_d}^2$ and m_S^2 by $M_Z, \tan \beta$ and μ_{eff} with the help of the minimization equations of the Higgs potential with respect to v_u, v_d and s .

For any choice of the parameters in the Lagrangian, the spectrum of the model can be computed with help of the code NMSSMTools [13, 14]; we employed the version 2.3.2 which is updated including radiative corrections to the Higgs sector from [15]. Only points respecting constraints on the Higgs sector from LEP and from B physics are retained. (Tevatron constraints are not relevant for the present region in parameter space.) The code also allows to compute the various Higgs decay branching ratios through a suitable generalization of HDECAY [16] to the NMSSM.

As discussed in the introduction, the Higgs sector of the NMSSM allows for relatively low values for the soft Susy breaking terms (and μ_{eff}) which must, however, respect constraints from unsuccessful direct searches for Susy particles. First results from the LHC [17–19] indicate that gluino and/or u- and d-squark masses are above ~ 700 GeV, whereas the t-squark masses (most relevant for the little finetuning problem in the MSSM) are not (yet?) constrained. For the specific example discussed below we make the following choice, motivated to a certain extend by the renormalization group running from the grand unification scale down to the weak scale (although the precise values are not important): gaugino masses $M_1=100$ GeV, $M_2=200$ GeV and $M_3=800$ GeV, squark masses of 800 GeV (but 600 GeV for the third generation), slepton masses of 200 GeV, $A_t = A_b = -300$ GeV, $A_\tau = -200$ GeV, $A_\lambda = 400$ GeV, $A_\kappa = -100$ GeV, $\mu_{eff} = 150$ GeV.

For the dimensionless parameters we take $\lambda = 0.634$, $\kappa = 0.3$ and $\tan \beta = 3.5$, but we get similar results (see below) for variations of the latter parameters within several %, and/or somewhat smaller or considerably larger dimensionful parameters. We did not look for a particularly low fine tuned region in parameter space, but content ourselves with the relatively low values for the soft stop mass terms.

For this choice of parameters, the masses of the two lightest physical CP-even Higgs states are

$$M_{H_1} \simeq 98 \text{ GeV}, \quad M_{H_2} \simeq 122 \text{ GeV}. \quad (3)$$

In addition there exist a singlet-like CP-odd Higgs state of mass ~ 180 GeV and a nearly degenerate multiplet of CP-even, CP-odd and charged Higgs states of masses ~ 500 GeV; these will play no role in the following.

The couplings of the Higgs states depend on their decomposition in the CP-even weak eigenstates H_d , H_u and S , which is given by

$$\begin{aligned} H_1 &\simeq -0.008 H_d - 0.60 H_u + 0.80 S, \\ H_2 &\simeq 0.33 H_d + 0.75 H_u + 0.57 S. \end{aligned} \quad (4)$$

Employing the notation $H_i = S_{i,k} H_k$ ($k = d, u, s$), the reduced tree level couplings (relative to a SM-like Higgs boson) of H_i to b quarks, t quarks and electroweak gauge bosons V are

$$\begin{aligned} \frac{g_{H_i bb}}{g_{H_{SM} bb}} &= \frac{S_{i,d}}{\cos \beta}, & \frac{g_{H_i tt}}{g_{H_{SM} tt}} &= \frac{S_{i,u}}{\sin \beta}, \\ \frac{g_{H_i VV}}{g_{H_{SM} VV}} &= \cos \beta S_{i,d} + \sin \beta S_{i,u}. \end{aligned} \quad (5)$$

Clearly, the reduced tree level coupling of H_1 to b quarks is very small for $S_{1,d} \simeq -0.008$. Squark/gluino loops can also contribute (notably for large $\tan \beta$) to the coupling of H_1 to b quarks via its $S_{1,u}$ -component [20–22]; in the present case the effective $H_1 bb$ coupling increases by just about 10% due to this phenomenon. Hence it is not astonishing that the partial decay width $\Gamma(H_1 \rightarrow b\bar{b})$ is strongly reduced with respect to a SM-like Higgs boson; in fact the dominant contribution (about 60%) to $\Gamma(H_1 \rightarrow b\bar{b})$ comes from the dominantly top-quark loop induced $H_1 gg^*$ coupling (where g denotes a gluon) and a subsequent $g^* \rightarrow b\bar{b}$ decay. All in all the total width of H_1 is smaller than the total width of a SM-like Higgs boson of similar mass by a factor ~ 0.04 .

The couplings of Higgs bosons to photons are induced by loop diagrams dominated by top-quark loops. Hence the coupling of H_1 is reduced by $\frac{g_{H_1 tt}}{g_{H_{SM} tt}} \simeq 0.63$ at first sight, but contributions from non-SM particles in the loops (mainly stop squarks) [23] increase $R_\gamma \equiv \frac{g_{H_1 \gamma\gamma}}{g_{H_{SM} \gamma\gamma}}$ to $R_\gamma \simeq 0.72$. Thus, although the partial width $\Gamma(H_1 \rightarrow \gamma\gamma)$ is smaller by a factor $R_\gamma^2 \simeq 0.52$ than the corresponding width of a SM-like Higgs boson, the branching fraction $BR(H_1 \rightarrow \gamma\gamma)$ is enhanced by a factor $R_\gamma^2/0.04 \simeq 12.7$, the result announced above. (The branching fraction of a SM-like Higgs boson of similar mass would be $BR(H_{SM} \rightarrow \gamma\gamma) \simeq 0.15\%$ [24].)

Altogether the relevant branching ratios of H_1 are given by

$$\begin{aligned} BR(H_1 \rightarrow gg) &\simeq 51\%, & BR(H_1 \rightarrow cc) &\simeq 35\%, \\ BR(H_1 \rightarrow b\bar{b}) &\simeq 9\%, & BR(H_1 \rightarrow WW) &\simeq 3\%, \\ BR(H_1 \rightarrow \gamma\gamma) &\simeq 1.9\%, & BR(H_1 \rightarrow \tau\tau) &\simeq 0.2\%. \end{aligned} \quad (6)$$

Next we turn to the production cross section for H_1 , again relative to the one of a SM-like Higgs boson. The dominant Higgs production process is via gluon-gluon fusion where, as stated above, the Hgg coupling is induced dominantly by a top-quark loop. Whereas this contribution is reduced by the factor $\frac{g_{H_1 tt}}{g_{H_{SM} tt}} \simeq 0.63$ as in the case of the $H_1 \gamma\gamma$ coupling, stop

loops [23] and the missing negative contribution from b quarks (for $M_H \sim 100$ GeV [24]) lead to a value for $R_g \equiv \frac{g_{H_1 gg}}{g_{H_{SM} gg}}$ of $R_g \simeq 0.69$. Hence the production cross section for H_1 via gluon-gluon fusion is reduced by $R_g^2 \simeq 0.60$; a similar reduction by $\simeq 0.34$ occurs for the less important H_1 production process via vector boson fusion due to the reduced coupling of H_1 to electroweak gauge bosons. All in all the signal rate in $gg \rightarrow H_1 \rightarrow \gamma\gamma$ is thus still enhanced by a factor $0.43 \times 12.7 \sim 6$ relative to a SM-like Higgs boson of similar mass.

If we vary the dimensionless parameters in range $\lambda = 0.5 - 0.7$, $\kappa = 0.25 - 0.35$ and $\tan\beta = 3.2 - 3.5$, the mass of H_1 varies in the range $80 - 117$ GeV. For parameters outside this range the mass of H_1 can well be below 80 GeV. Then, however, LEP constraints imply a very large singlet component of H_1 (a reduced coupling to the Z boson) such that its production rate at the LHC becomes too small. Since $S_{1,d}$ can be larger and $S_{1,u}$ be smaller, the relative signal rate $R = \sigma(gg \rightarrow H_1 \rightarrow \gamma\gamma)/\sigma(gg \rightarrow H_{SM} \rightarrow \gamma\gamma)$ can vary from ~ 0 to ~ 6.5 , as shown for about 500 points in Fig. 1 satisfying LEP and all other phenomenological constraints. If R is small, the scenario can be similar to the difficult points discussed in [25] where a high luminosity run of the LHC is required in order to detect at least one Higgs boson of the NMSSM, even though Higgs-to-Higgs decays are not relevant: due to its reduced couplings, the production rate of H_2 will be strongly reduced *without* an enhanced branching ratio into two photons (of just 0.068% here). H_2 would be most visible in vector boson fusion and its decay into two tau leptons but, according to our estimate, more than $\sim 200 \text{ fb}^{-1}$ would be required for its 5σ detection.

The range of $97 - 108$ GeV for M_{H_1} , where R can be $\gtrsim 5$, overlaps with the range where a light excess (of about 2σ significance) has been observed in the $b\bar{b}$ final state at LEP [5]. Here constraints on Higgs bosons with reduced couplings to the Z boson are relatively weak. Clearly, the contribution of the state H_1 to the LEP signal would be quite small for a reduced branching fraction into $b\bar{b}$ together with the reduced coupling to the Z boson. Still, including the $H_1 \rightarrow gg^* \rightarrow gbb$ channel, the signal rate at LEP for the points with $R \gtrsim 5$ in Fig. 1 can be about 10% of the one of a SM-like Higgs boson (possibly enhanced by mis-tagged gluon or charm jets). If we require at least 5% for this relative rate, the points with $R \sim 0$ in Fig. 1 (where H_1 is very singlet-like) disappear. Note that, due to the absence of corresponding contributions from the gg^* channel, the expected excess in the $\tau\tau$ final state is smaller in agreement with the observations [5].

3 Conclusions and outlook

We have found that a significant excess of the signal rate in $gg \rightarrow H_1 \rightarrow \gamma\gamma$ up to a factor ~ 6 with respect to a SM-like Higgs boson is possible in the NMSSM, remarkably for an unexpected mass range $M_{H_1} \lesssim 110$ GeV. These scenarios are not far-fetched, since they are possible for a relatively low Susy breaking scale and motivated, to some extent, by LEP results. (Searches for “fermiophobic Higgs bosons” decaying dominantly into two photons had also been performed at LEP [26]. However, the upper limits on $\sigma(h) \times BR(h \rightarrow \gamma\gamma)/\sigma(h)_{SM}$ of 1% – 6% do not exclude the scenarios studied here.)

At present, using data up to 5.4 fb^{-1} , the CDF and D0 groups at the Tevatron exclude to 95% C.L. a signal in the $\gamma\gamma$ final state if it is about 20 – 25 times as large as the one of a SM Higgs boson for $M_H > 100$ GeV [27–29], hence beyond a possible signal within the

present scenario.

At the LHC with 7 TeV c.m. energy and an integrated luminosity of 1 fb^{-1} , the ATLAS [30] and CMS [31] groups expect 95% C.L. exclusion limits at about 4 times the SM Higgs signal rates for $M_H > 110\text{--}115 \text{ GeV}$. If the corresponding curves are extrapolated naively down to $M_H \sim 100 \text{ GeV}$, the exclusion limits should still be better than 6 times the SM Higgs signal rate for this mass range. However, the present results should motivate the experimental groups to extend their analyses to lower Higgs masses in the $H \rightarrow \gamma\gamma$ mode, even if these are seemingly excluded by LEP. At least for 14 TeV c.m. energy and an integrated luminosity of 30 fb^{-1} , signals for a low mass Higgs boson are well possible in the NMSSM in this channel.

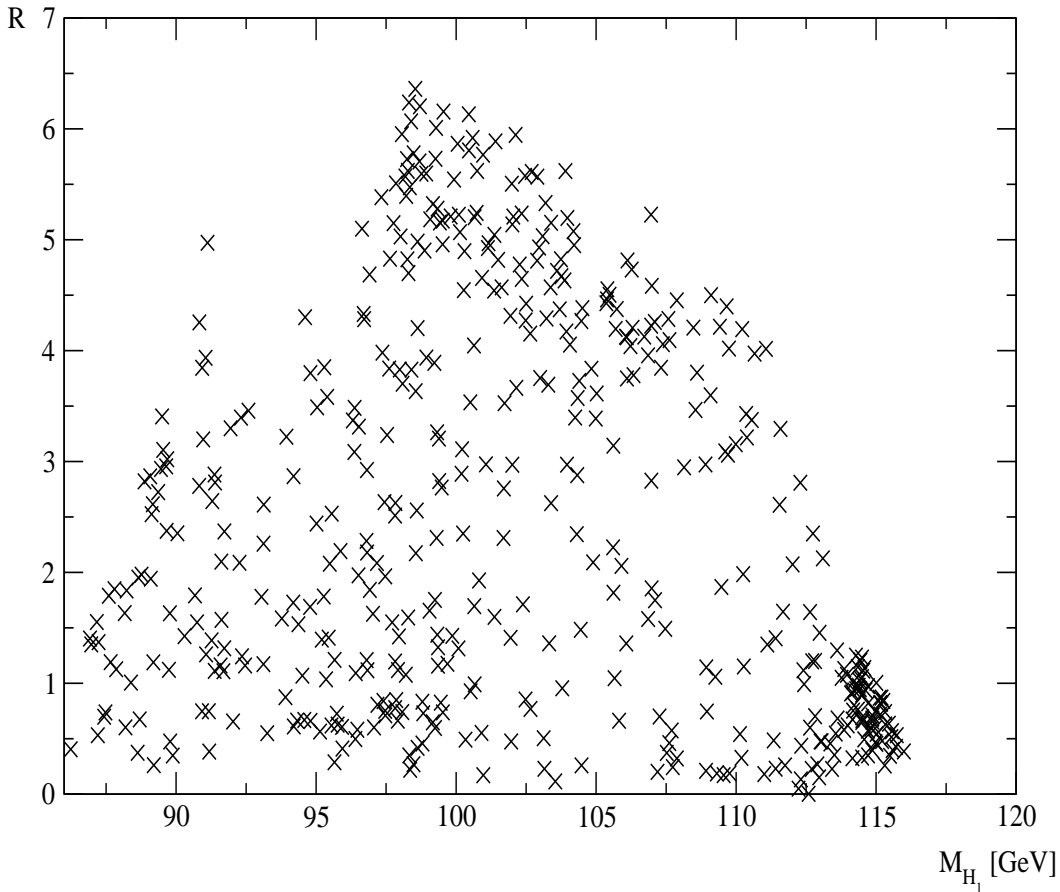


Figure 1: The relative signal rate $R = \sigma(gg \rightarrow H_1 \rightarrow \gamma\gamma)/\sigma(gg \rightarrow H_{SM} \rightarrow \gamma\gamma)$ as function of M_{H_1} for about 500 points in the parameter space of the NMSSM

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